COMPUTER SCIENCE & TECHNOLOGY:

FOREIGN AND DOMESTIC ACCOMPLISHMENTS IN MAGNETIC BUBBLE DEVICE TECHNOLOGY

NBS Special Publication 500-1
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COMPUTER SCIENCE & TECHNOLOGY:

Foreign and Domestic Accomplishments in Magnetic Bubble Device Technology

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PREFACE

This document assesses the status of magnetic bubble technology as displayed by foreign research and manufacturing facilities. Japanese and Western European capabilities and accomplishments in magnetic bubble technology are compared to the United States position. Both technical and economic factors are addressed and described. Conclusions suggesting future impacts of magnetic bubble memories on computer technology are presented.

Information contained in this report was derived from the open technical literature and from private interviews with various U.S. technical experts. Where possible, references in the open literature are cited, although the opinion of technical experts were checked in order to substantiate certain points.

The technology assessment resulting in this report was conducted by the Information Technology Division of the Institute for Computer Sciences and Technology, National Bureau of Standards, as part of an "Advanced Computer Technology Survey" project. Mr. Robert B. J. Warnar was the principal technical investigator and was responsible for the preparation of this report. He was assisted by Mr. Peter J. Calomeris. Mr. Sidney B. Geller of the Computer Engineering Division served as technical consultant. Editorial assistance was provided by Mr. Edwin J. Istvan, Acting Chief of the Information Technology Division, and by Mr. George E. Lindamood, Project leader.

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FOREIGN AND DOMESTIC ACCOMPLISHMENTS IN MAGNETIC BUBBLE DEVICE TECHNOLOGY

Robert B. J. Warnar
Peter J. Calomeris

ABSTRACT

This document assesses the status of magnetic bubble technology as displayed by non-U.S. research and manufacturing facilities. Non-U.S. research and U.S. accomplishments are described while both technical and economic factors are addressed. Magnetic bubble devices are discussed whenever their application could impact future computer system design. Generally the magnetic bubble device can be applied to a computer system as a peripheral mass memory. Magnetic bubble devices are produced from either synthetic garnet or amorphous materials rather than from familiar silicon material. The document contains a significant bibliography to support certain main points which are supplemented by information supplied by the library of the Information Technology Division (ICST-NBS) and from private interviews with various U.S. technical experts.

Key words: Amorphous materials; bubble; field-access; garnet; guide-pattern; magnetoresistance; nonvolatility; orthoferrite; photolithography; uniaxial structures.

1. MAGNETIC BUBBLE DEVICE OVERVIEW

Magnetic Bubble Technology

Magnetic bubble devices utilize the mobile properties of cylindrical magnetic domains. Early this century, spontaneously magnetized crystalline structures (domains) were found to exist in metals such as iron, cobalt, and nickel. The magnetizations of these domains were randomly aligned in all directions. This randomness is typical in polycrystalline materials. [1]

Early experimenters found that polycrystalline magnetic properties were difficult to control. Ensuing experiments with single crystal magnetic material, which have magnetic moments that are aligned with each other (uniaxial structures), demonstrated properties which were relatively easy to manage. [2]

Manageability of the magnetic properties within the uniaxial films (usually consisting of magnetic oxides) is greatly facilitated by the use of a microscope setup which permits visual observation of the magnetic domains by exposing the relatively transparent oxides to polarized light. The Faraday effect causes the plane of polarization of the light to rotate, depending on the direction of magnetization of the domains located in the oxide film. The microscope setup allows the experimenter to distinguish the magnetic domains with their magnetic moments pointing upward from those with their magnetic moments pointing downward. Faraday effect observations reveal that magnetic domains within the ferromagnetic oxide films look like randomly oriented worm-like strips when the films are not in a magnetic field. When a magnetic field is applied perpendicularly to the plane of oxide, it causes the magnetic strips to contract and divide into little circular islands initially described as "magnetic soap bubbles." These "bubbles" are actually cylindrically shaped domains which extend through the entire thickness of the film. The trace of the cylinder top on the surface of the film is perceived as a circle under Faraday effect observation. These circles are what eventually became known as "magnetic bubbles." [3,4]

Although many scientists became active in researching these uniaxial bubble domain properties, the major breakthrough was made by A. H. Bobeck (Bell Telephone Laboratories) in 1967. Bobeck introduced the idea that the magnetic bubble must be magnetized normal to the surface of the oxide in which it is located. Experiments verified this and Bobeck then showed that it was possible to move the bubbles in any direction within the plane of the oxide ($YFeO_3$) film by the application of a proper external magnetic field. [5]

From the time of Bobeck's breakthrough until now, orthoferrites, garnets, and amorphous materials have been studied for application in magnetic bubble devices. During the history of material research, (totally different in concept than the familiar silicon technology approach), dozens of experimental bubble devices using many types of guide patterns (which are used to provide pathways for bubbles) were invented by material researchers. [1]

Magnetic Bubble Device Characteristics

Magnetic bubble research and development has been evident for the past ten years. However, as of today, no standard materials, methods of bubble propagation, chip size or chip capacity, power supply voltages, etc., are visible among laboratory models. Furthermore, no commercial devices can be found as yet in the stock of electronic wholesale houses although several special purpose bubble memory systems have been delivered such as those by Rockwell International to NASA for use in space recorders. [6]

According to some expert technology forecasters, if magnetic bubble devices are to survive, manufacturers must enter their products into the commercial markets as soon as possible after the device conception and characterization is completed. This is the tradition in the semiconductor device technology.

The following manufacturers, both U.S. and foreign, are some of the foremost developers of magnetic domain or bubble materials or devices: [7]

Bell Telephone Laboratories (BTL)
Cambridge Memories (in connection with Crouzet, France)
Hewlett-Packard (HP)
International Business Machines (IBM)
Monsanto
North American Rockwell Electronics (NARE)
Texas Instruments (TI)
Univac
Crouzet, SA (France)
Plessey Microsystems (England)
Philips Gloeilampen Fabrieken (The Netherlands)
Siemens (Germany)
Fujitsu Laboratories, (Japan) Ltd.
Hitachi (Japan) Ltd.
Kokusai Denshin Denwa Co. (KDD - Japan)
Nippon Electric Co. (NEC - Japan) Ltd.
Nippon Telephone and Telegraph Public Corp. (NTT - Japan)
Tohoku Metals Industries (Japan)
Tokyo Shibaura Electric Company, (Toshiba - Japan) Ltd.

Scientists associated with the above research and manufacturing facilities have published articles which indicate numerous favorable bubble characteristics. Arthur D. Little, Inc., has accumulated a great deal of information on the various characteristics of magnetic bubble devices; some of these are: [7]

High function packing density
Nonvolatility
Destructive and nondestructive data operation
Bidirectional register operation
Low energy dissipation
Negligible standby power operation
High resistance to shock and vibration
Relative light weight construction
Low volume construction
Storage, switching and logic function operation
Material impurity resistance
Radiation resistance
Synchronous and asynchronous operation
Visible device operation (via special microscope setup)
Potential low cost production
Parallel function operation

High data-storage-density, low power operation, good production yield, non-volatility, and radiation resistance are the outstanding desirable characteristics of the magnetic bubble device. Bit-storage-density of a future magnetic bubble memory system could become as high as one billion bits per square centimeter. Generally, it appears that bubble density is limited primarily by the fabrication techniques in deposition of small guide patterns and detectors rather than the actual size of the bubbles. The closest developing, competing technology, charge-coupled devices, will have great difficulty in approaching such densities at comparative yields. [8]

Most of the power required to propagate bubbles is dissipated in the elements which produce the magnetic fields that move the bubbles along their guide pattern paths. Experiments show that small bubbles require less propagation power than the larger bubbles. Consequently, the smaller the bubble, the greater the density and the less power per bubble is required. In addition, some smaller bubbles are capable of moving at higher velocities. Experimental bubble memories are capable of operating at 10 nanowatts per bit; a figure which semiconductors will find hard to compete with.

Despite the attractive bubble device features, several drawbacks deter bubble device production: [7]

Temperature sensitivity
Relative poor signal-to-noise ratio
Lack of standard material
Low voltage interface
Serial memory operation
Low speed data rate
Limited production technology

Slow data rate, serial data access, and temperature limitations are the most serious of these drawbacks. After ten years of bubble research, most laboratory memory models cannot exceed a data rate of one megahertz (1 MHz) under favorable temperature conditions. Other memory devices such as crossties, semiconductors, and optical memories are expected to be faster than the magnetic bubble memory and are intrinsically less sensitive to temperature.

Magnetic bubble materials, such as garnets, require doping by several elements to reduce undesirable characteristics such as temperature sensitivity and low speed operation. By comparison, silicon usually requires doping by only one element. [9]

Fortunately, bubble device research facilities are able to make use of several fabrication and production processes which are already established in the silicon technology. Photo, E-beam, and X-ray lithography and ion implantation techniques can be applied to bubble hosts. However, the utilization of these existing fabrication techniques does not guarantee that bubble characteristics are exploited to their fullest extent. If bubble devices are to realize their fullest potential, fabrication techniques capable of producing micro-miniature circuits of one to two orders smaller than are presently available will be necessary. In the meantime, viability of the bubble device could very well depend on technical acceptance by the electronic market rather than on device performance. [8, 10]

Technical Obstacles in Magnetic Bubble Devices

The most severe obstacle in the development of magnetic bubble devices is the requirement for the use of relatively new garnet materials rather than the use of well-developed silicon materials. [6, 11]

The second obstacle is the reluctance of equipment manufacturers to accept an unproved memory device.

The third obstacle is the combination of several undesirable technical characteristics which are inherent to magnetic bubble devices: temperature sensitivity, low speed, and low-signal-level operation. It is anticipated that the temperature problem will eventually be solved. The low speed, low-signal-level operation problems of bubbles are considered the most difficult obstacles by scientists and keep the magnetic bubble memory from becoming a large, fast random access memory. [7]

To overcome these obstacles, magnetic bubble device manufacturers must offer compensating device features such as super-high bit-storage-density, ultralow power operation, and low cost. Currently, such goals have not been attained, and magnetic bubble devices are therefore not competitive with other more developed technologies such as silicon devices and some mechanical memories.

It is concluded that magnetic bubble devices will eventually gain acceptance as block-oriented, random access memories in computer systems. In this role, magnetic bubble memories will eventually replace mechanically operated peripheral memories such as disks and drums. [7, 16]

Magnetic Bubble Device Applications

Foreign literature suggests several applications for the bubble memory. The following listing suggests how foreign magnetic bubble memory manufacturers plan to apply their products:

- Japan - Telephone and television applications. [12]
- England - Mass memory systems aimed at the bank data capture systems, computer cache memories. [13]
- France - Digital television systems, avionic displays, high performance digital recorders, satellite memories, and small disk replacement memories. [14]

- The Netherlands - Digital recording systems. [15]

- The Federal Republic of Germany - Disk and drum replacements. [16]

Some potential applications, mentioned in the researched literature, are: [8, 17]

- Portable (including pocket-type) calculators

- Intelligent terminals

The integration of magnetic bubble memories into pocket calculators would improve processing capacity tremendously. Calculators would be able to store large programs, possibly loaded via telephone lines from distant host computers. (Currently available programmable hand calculators are programmed only by the insertion of various magnetic, programmed strips. Each program requires a different strip and the contents of the calculator memory are lost when the power is turned off.)

The described magnetic bubble memory calculator should incur very little service computer usage cost since the connection period to the service computer can be short and infrequent. The increase of cost of the hand calculator can therefore be tolerated since the increased processing power of the calculator makes the unit capable of meeting many "costly terminal" requirements. [8, 17]

The features of a future, readily available, and easily adaptable hand calculator are:

- Improved Portability - afforded by the low power operation of magnetic bubble memories;

- Increased Processing Power - obtained through the use of both vast bubble memory and silicon microprocessors; and

- Permanent Program Retention - allowed by the nonvolatility of magnetic bubble memories.

In the case of the intelligent terminals, the use of large magnetic bubble memories can be extremely cost-effective in the long run. The reduction of operation costs occurs because large programs and data bases can be maintained within the terminal.

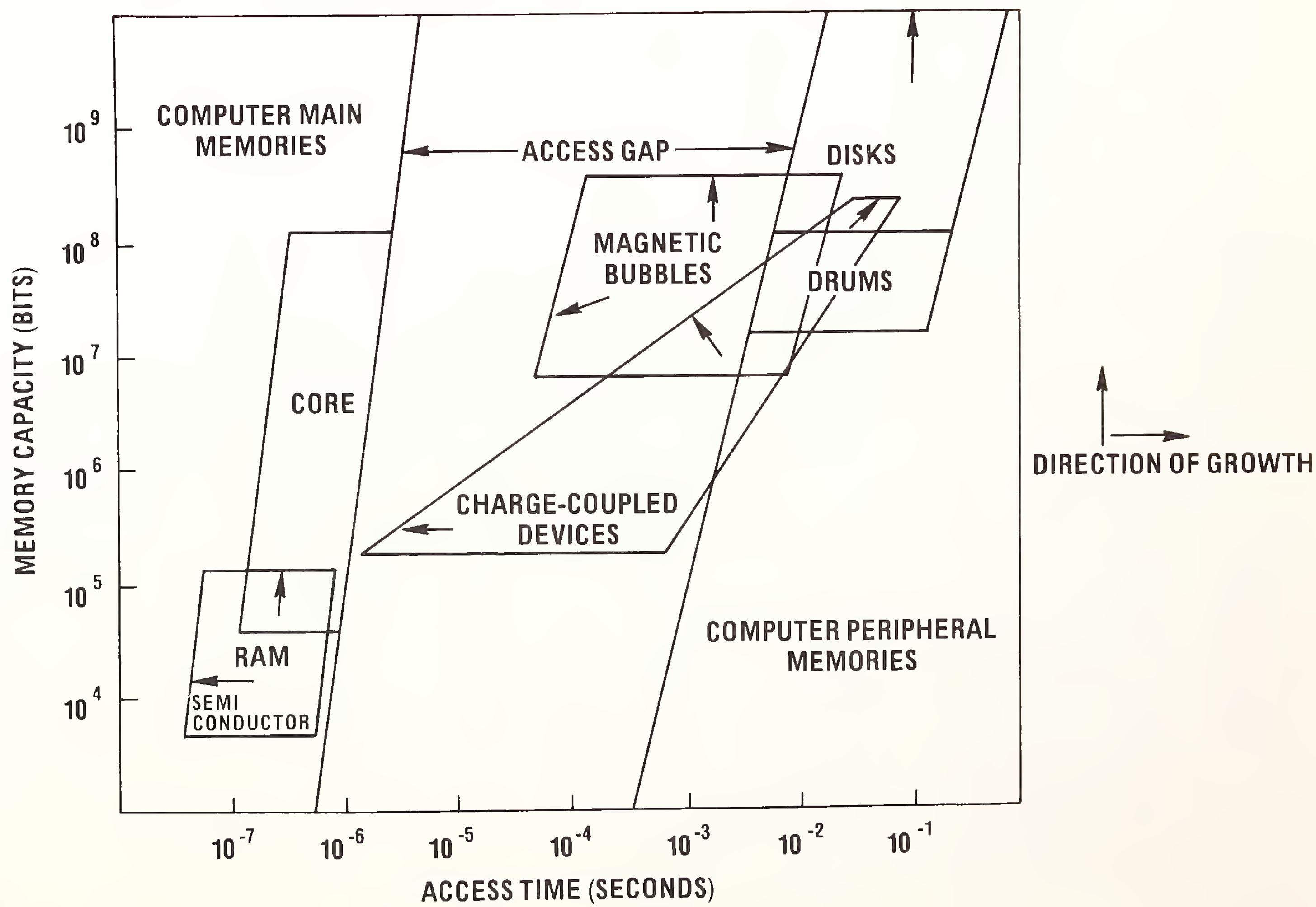
The current influx of microprocessors into intelligent terminals will also result in the demand for more memory. Foreign manufacturers like Hitachi, Philips, Bell Northern Research of Canada, and Plessey Microsystems are all producing their own microprocessors or microcomputers.

Memory Application Trends

At present, bubble devices could be implemented in the computer as memories located between the fast main memory and the external mass memory. Device application in this area is presently competed for by charge-coupled devices, crossties, and other exotic memories such as potassium nitrate (KNO_3) devices.

The "Memory Access Gap" shown in Figure 1, reflects the differences in characteristics between computer main memory and peripheral mass memory. Some foreign and U. S. manufacturers are seeking to narrow the access gap by substituting magnetic bubble mass memories in place of peripheral mass memory devices such as disks and drums. Such substitution may become commercially viable within the next five years since silicon device mass memories are still rare; slow serial read-out operation is common; and operational requirements are not terribly stringent. [18]

FIGURE 1 — THE MEMORY ACCESS GAP



Future Magnetic Bubble Memory Design

For market acceptance, magnetic bubble memory manufacturers must further develop their products to a point at which the advantages of magnetic bubbles over other technologies are clearly evident. This is presently not the case. The magnetic bubble memory characteristics that must be further developed are bit-storage-density and memory access time paired with low cost per memory bit. [6, 19]

According to some technology forecasters, magnetic bubble memories must be able to compensate with higher speeds to offset their higher costs when compared with mechanical memory technologies to gain acceptance in the marketplace. A factor of ten-to-one in speed is quoted to offset the current ten-to-one cost differential. [8, 10, 20]

Specifications for a future cost-effective magnetic bubble memory that could find a favorable market are presented in Table 1.

2. MAGNETIC BUBBLE PARAMETERS

Magnetic Bubble Materials

Since the discovery of the magnetic bubble, researchers have been involved in the task of determining which magnetic material is best suited for use in producing devices. Most of the materials used for magnetic media contain rare earths. The inclusion of these elements produces magnetic media with the desirable magnetic properties. [1]

Magnetic bubble materials should be low cost, readily available, and should exhibit the following characteristics:

a. Stable magnetic axes as a function of temperature, humidity, etc.

b. Easily workable crystal structures.

As the result of much research, three groups of materials have emerged as candidates for magnetic media:

a. Orthoferrites [21]

b. Garnets [22, 23, 24, 25, 26, 27]

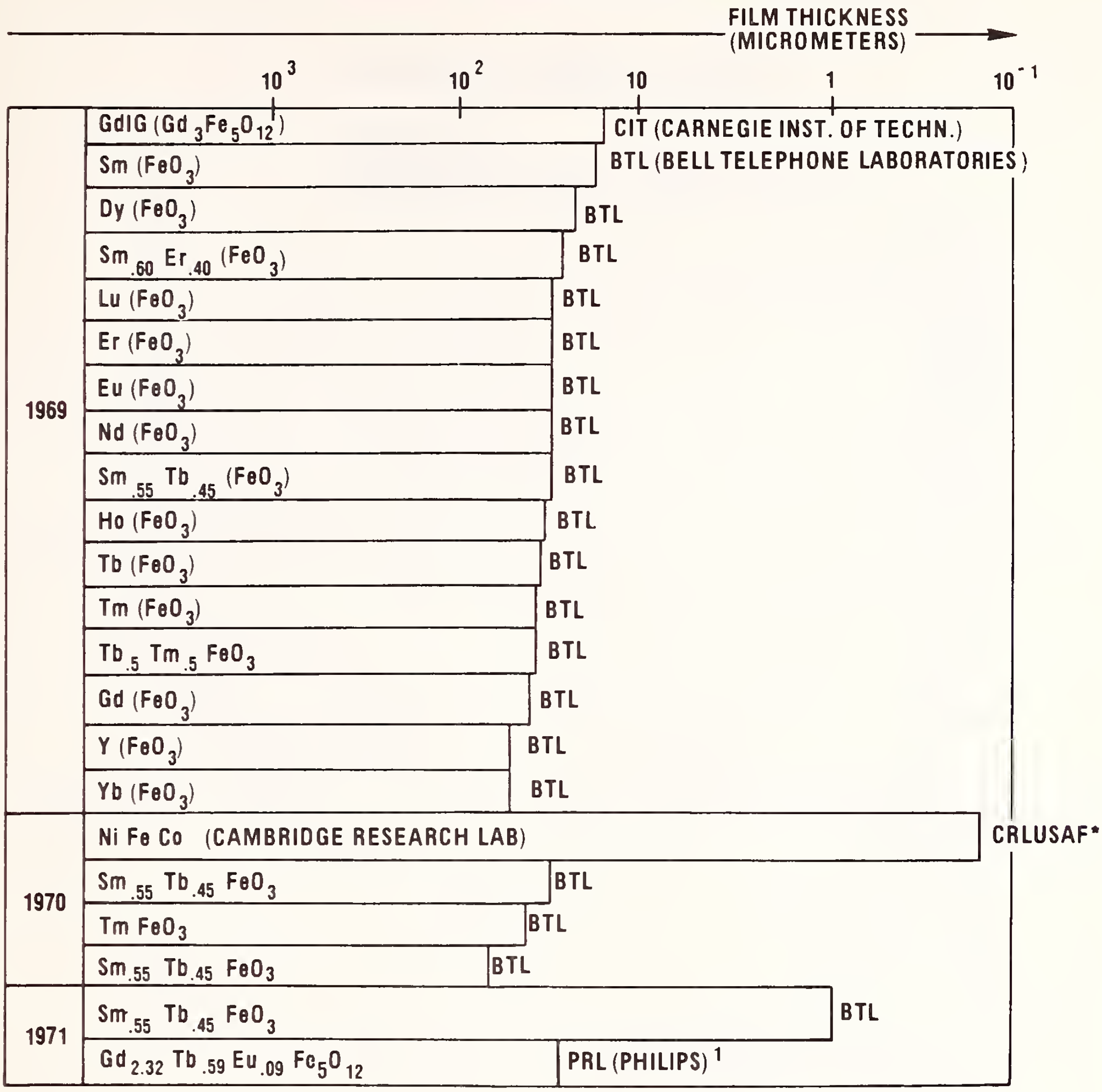
c. Amorphous film materials [28, 29, 30]

Orthoferrites are characterized by the formula $A\ Fe\ O_3$, where A can be an element similar to any of those used in garnets. The general formula for garnets is $A_3\ B_5\ O_{12}$, where A and B are different types of elements with A being a large radius ion such as any of the rare earths and B a smaller radius ion such as any of the transition metals like iron (Fe). Amorphous films are unlike garnets and orthoferrites since they exhibit noncrystalline structures. The amorphous films are composed of metals such as cobalt and certain rare earths like gadolinium (Gd). [29, 31]

Table 1 - Specifications for a Future Magnetic Bubble Memory Device

Bit Storage Capacity	Word Length	Access Time	Power Dissipation	Signal-to-Noise Ratio	Power Supply Requirements	Input/Output Circuitry
1 million bits or better	16 bits parallel	0.1 milli-second to any word	< 5 watts operating; 0 watts in standby	30 decibels or better	+ 5 VDC. ± 0.5 VDC	On-chip bi-directional data-bus design
Digital Interface Signal Levels	Operating Temperature Range	Package Form	Memory Storage Characteristic	Address Decoding Circuitry	Cost Per Bit	Cost Per Device
0 volts = 0 + 5 VDC, ± 0.5 VDC = 1	0° C to + 100° C (-55° C to +125° C for special applications must be available)	Dual-In-Line or Quad-In-Line Package	Nonvolatile data retention	Address decoding circuitry must be an on-chip design	< 1.0 milli-cent	$10 (In quantities of 100 or less)

MAGNETIC BUBBLE MATERIALS



*DOMAIN TIP MEMORY

[1] THE NETHERLANDS

FIGURE 2 (a)

MAGNETIC BUBBLE MATERIALS

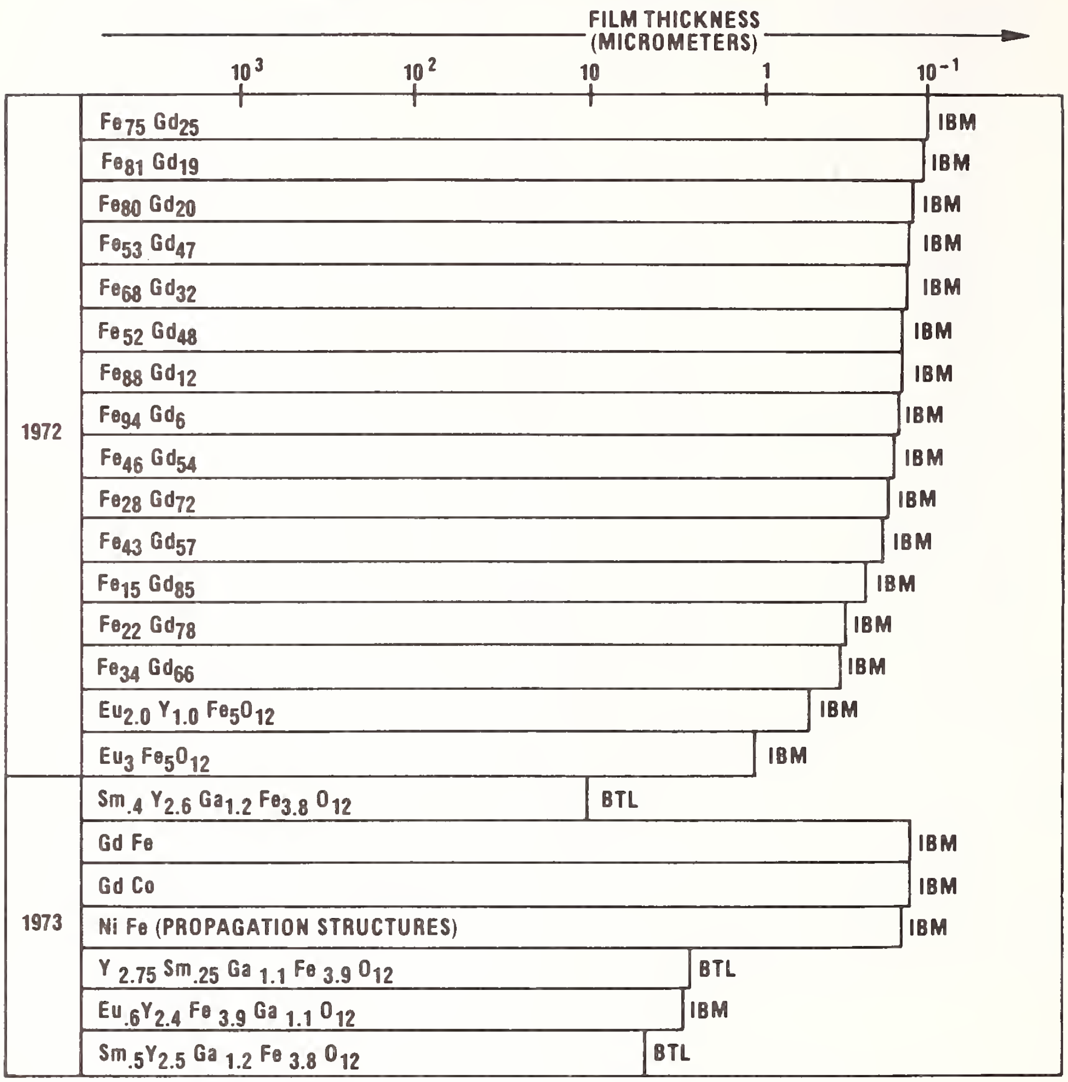
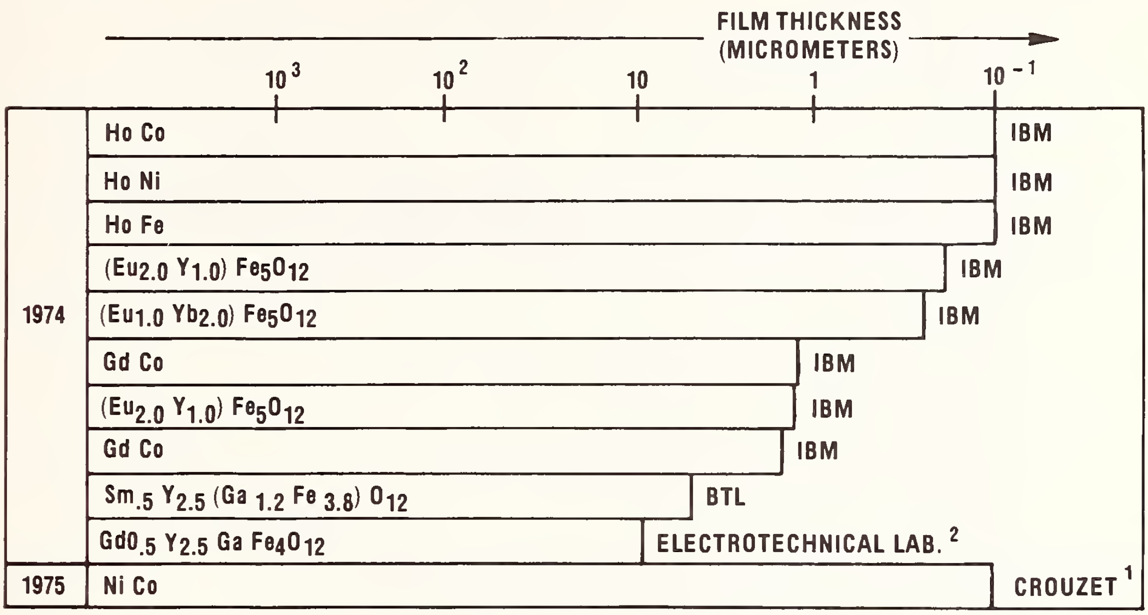


FIGURE 2 (b)

MAGNETIC BUBBLE MATERIALS



[1] FRENCH
[2] JAPANESE

FIGURE 2 (c)

DIAMETERS OF MAGNETIC BUBBLES (MICROMETERS)

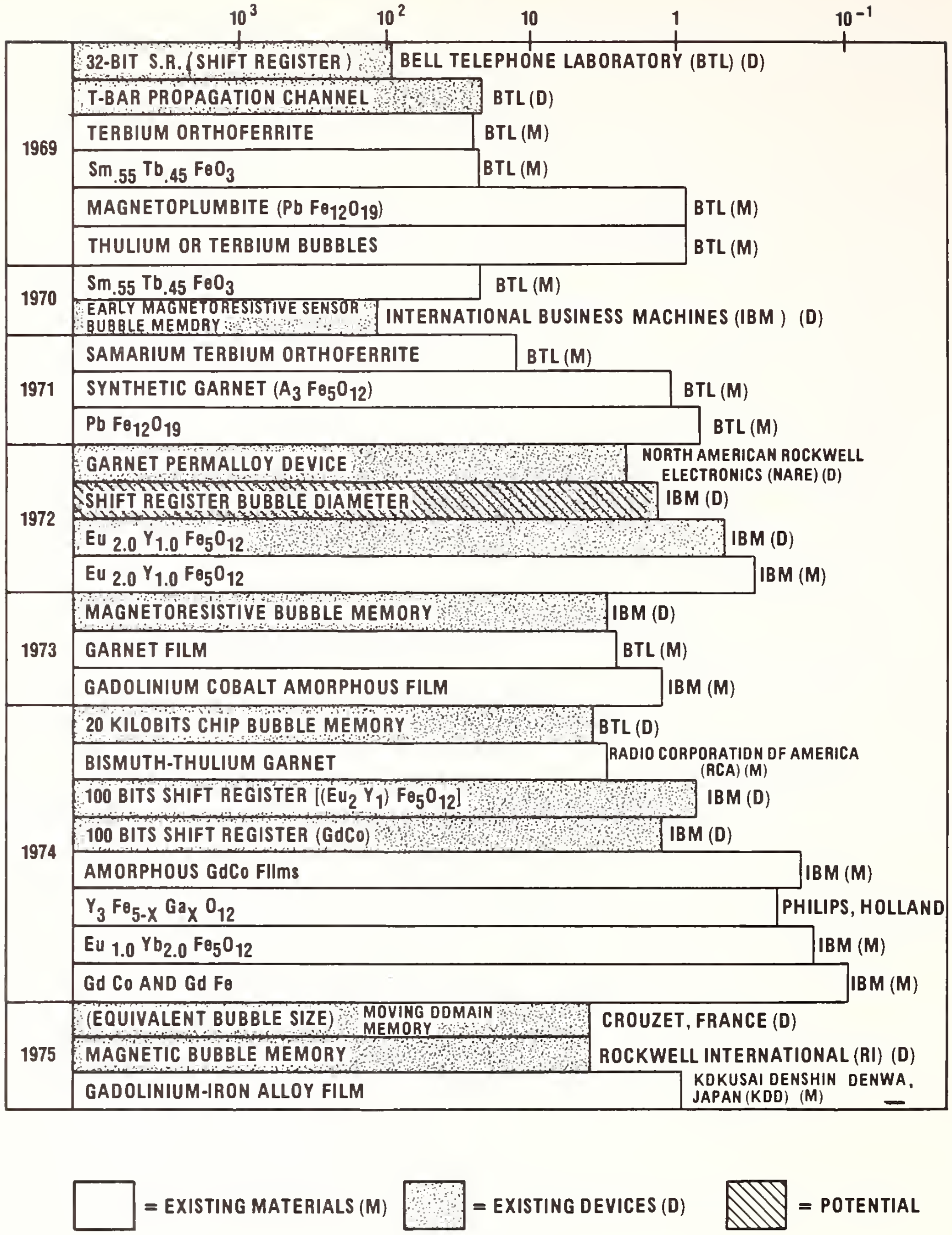


FIGURE 3

Figures 2a, b, and c provide a historical overview of some materials used since 1969. The material is identified by its formula, its research facility, its thickness, and the year in which the article containing the information was published. The Figures 2(a), (b), and (c) show garnets in 1971 ($Gd_{2.32}\ Tb_{.59}\ Eu_{.09}\ Fe_5\ O_{12}$), in 1972 ($Eu_3\ Fe_5\ O_{12}$) and in 1974 ($Sm_{.5}\ Y_{2.5}\ Ga_{1.2}\ Fe_{3.8}\ O_{12}$). In 1969 we find an orthoferrite in the form of $Tb_{.5}\ Tm_{.5}\ Fe\ O_3$ and in 1971 another by the formula $Sm_{.55}\ Tb_{.45}\ Fe\ O_3$. Amorphous films such as Gd Co and Gd Fe were produced in 1972 through 1974 and generally exhibited better magnetic bubble device properties than orthoferrites. [32]

Facilities in France are experimenting with nickel-cobalt films in their moving domain memories (MOD) whose material formula is shown as Ni Co for the year 1975. Other companies are producing magnetic bubble chips from the garnet formula $Gd_{0.5}\ Y_{2.5}\ Ga\ Fe_4\ O_{12}$, which is shown in the Figure 2(c) graph for the year 1974. [9, 14, 33]

As a whole, it appears that garnets are used more now than other materials by various research facilities even though amorphous films appear to have greater potential in bubble density.

Magnetic Bubble Diameters

As previously mentioned, magnetic bubbles behave like magnetic domain cylinders. Experiments indicate that the smallest diameter of a cylinder with acceptable stability is obtained when it approaches the dimension of the film thickness. Thus, if bubbles, supported by small bubble guides, are very small and the magnetic film is very thin, the amount of data which is stored per given area can be high. Therefore, not only bubble device properties but also the fabrication techniques of the materials determine the storage densities. [2]

Figures 2 and 3 indicate some of the relationships between film thickness and bubble diameter. Figure 3 summarizes the range of bubble diameters for various materials and presents a history of technological developments from 1969 to the present time (1975). Currently, the bubble diameter seems to be somewhere in the vicinity of 10^{-4}cm or 1 micrometer while the film thickness is slightly less.

The diameter of the domain can be made to vary from that of a strip domain to a magnetic bubble cylinder with a diameter of less than 1 micrometer by increasing the perpendicular magnetic field. If the magnetic field is increased to a critical value which depends upon magnetic characteristics of the bubble host material, the bubble collapses. A "safe" value for a stable bubble is one which is about twice the diameter of the magnetic bubble before collapsing. [21, 32]

Amorphous films have been produced with bubble diameters smaller (0.1 micrometer) than garnets. According to the graph, Philips and some U.S. companies have achieved some of the smallest bubble diameters in garnets (0.5 micrometers). [27, 34]

Magnetic Bubble Memory Storage Density

A superior characteristic of magnetic bubbles over alternative memory technologies is their potentially high information-storage-density. Experts predict that bubble density will surpass 10^{11} bits per square centimeter (as compared to 10^8 bits for semiconductors). The primary limitation of bubble density is the fabrication process. The limits of photo, E-beam, and X-ray lithographic processes have been under constant study while the latest magnetic bubble research breakthroughs have occurred by the use of ion implantation processes. [8]

Figure 4 provides a historical overview of how magnetic bubble density has progressed through the years from 1969 to the present. Initially, bubble materials had densities of 10^4 to 10^5 bubbles per square centimeter in orthoferrites. Predictions for other prospective materials were as high as 10^7 bubbles, or bits, per square centimeter. [7]

DENSITIES OF MAGNETIC BUBBLES
(BITS/CM²)

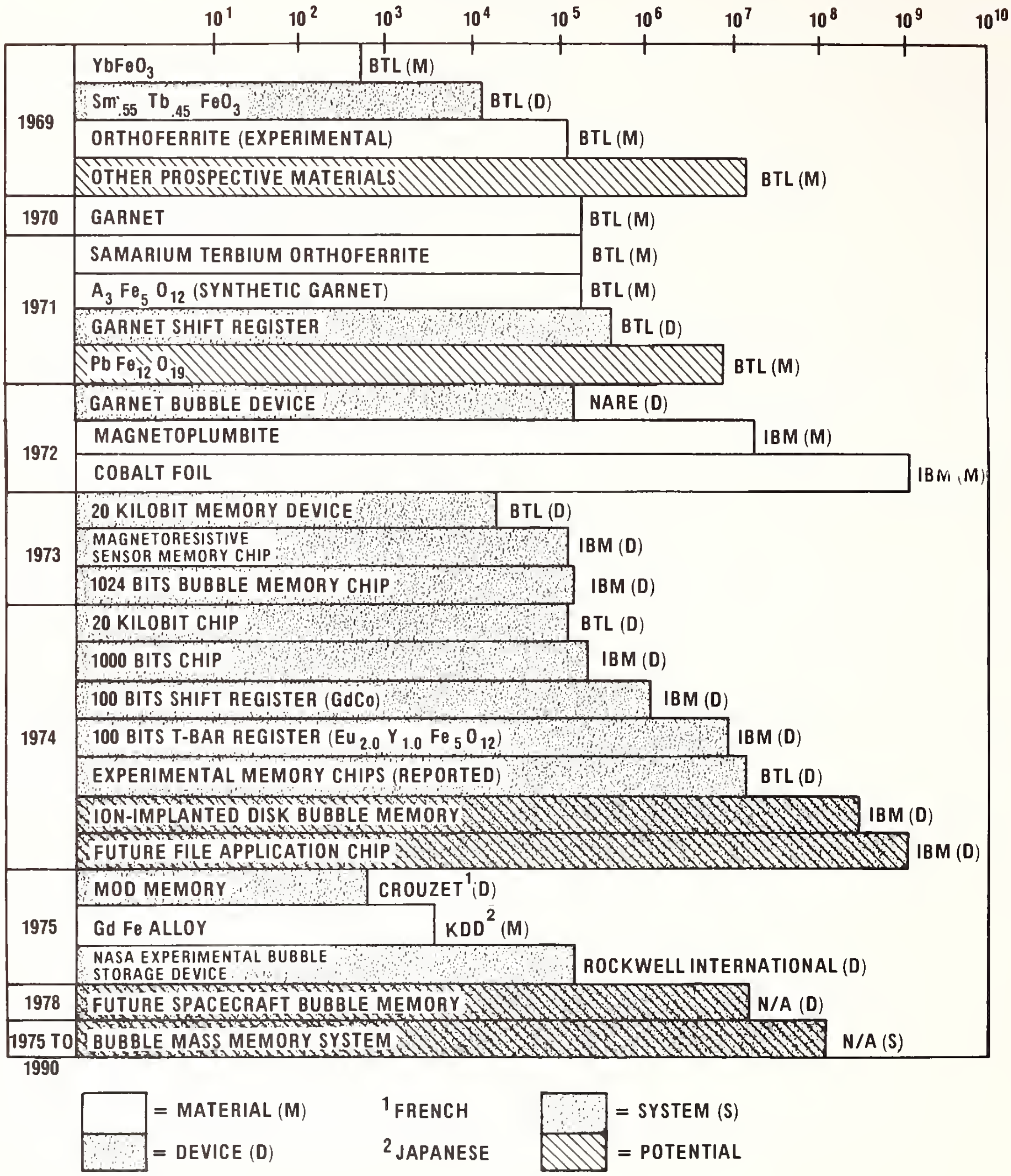


FIGURE 4

In 1970, 1971, and 1972, garnet materials were developed which exhibited equal or better magnetic and physical properties than orthoferrites. The average density for both materials is now somewhere between 10^5 and 10^7 bits per square centimeter. One research facility reported densities of 10^9 bits per square centimeter in cobalt foil materials in 1972.

It must be noted that high bit-storage-densities in materials have not always enabled the production of high bit density devices (such as memories). The additional area required by bubble guides and detectors almost always drastically reduce chip-bit densities.

Magnetic Bubble Chip-Bit Densities

Figure 5 shows magnetic bubble laboratory devices that have been produced by various manufacturers. The chip-bit densities are indicated for each device progressively from 1969 to the present, (1975). [35, 36]

Magnetic Bubble Velocities

Figure 6 indicates how fast bubbles move through materials. The speed of the bubble is usually a compromise between low material coercivity and high bubble stability. As shown in the Figure, bubble speed has increased steadily, but not drastically, from 1970 to 1975. Some of this increase in speed has been achieved through the use of improved magnetic bubble materials. In general, garnets can have higher bubble speeds than either ferrites or orthoferrites. [15, 37]

Magnetic Bubble Data Rate and Access Time

The data rate of magnetic bubbles is measured in bits per second and relates to the rate at which data propagates through either the material or device, as presented in Figure 7. This Figure shows the trend of increasing speed of data propagation from 1969 to present.

The data presented in this Figure also suggest that research facilities first develop high data rate materials and then try to develop independent devices. [38]

Access time is related to data rate since bubble memories are serial devices. For example, the average access time for a 2048-bit serial bubble memory operating at a 500 KHz clock rate is determined by the following formula:

$$\text{T-access (average)} = \frac{1}{\text{(Bubble Propagation Rate)}} \times \frac{\text{Number of bubbles per device}}{2}$$

$$= \frac{1}{(5 \times 10^5 \text{ bits/sec})} \times \frac{2048 \text{ Bubbles}}{2} = 2048 \text{ microseconds}$$

The worst access time occurs when the required data have just left the detector and must travel the entire register again. The worst access time is twice the average access time. Obviously, the best access time occurs when the data are just about to arrive at the detector, i.e., one clock cycle away from the detector.

Since bubble memories are characteristically serially oriented, bubble devices will usually be comprised of several optimum length registers in one chip. In this approach, storage capacity can be great and the access time will be only slightly greater than the access time of one single register. The slight increase in time results from the additional time needed to choose which register is being addressed. [39, 40]

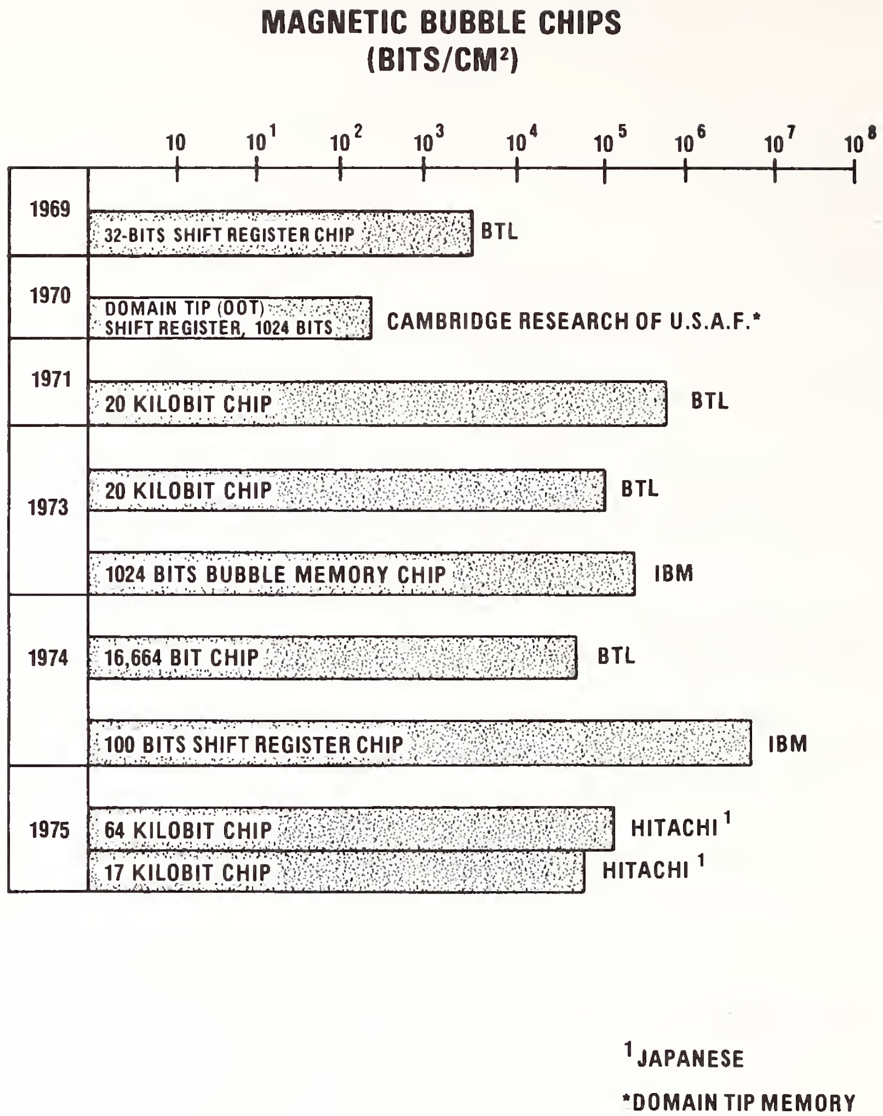

MAGNETIC BUBBLE CHIPS
(BITS/CM²)
10
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
1969
32-BITS SHIFT REGISTER CHIP
BTL
1970
DOMAIN TIP (DOT)
SHIFT REGISTER, 1024 BITS
CAMBRIDGE RESEARCH OF U.S.A.F.*
1971
20 KILOBIT CHIP
BTL
1973
20 KILOBIT CHIP
BTL
1024 BITS BUBBLE MEMORY CHIP
IBM
1974
16,664 BIT CHIP
BTL
100 BITS SHIFT REGISTER CHIP
IBM
1975
64 KILOBIT CHIP
HITACHI [1]
17 KILOBIT CHIP
HITACHI [1]
[1] JAPANESE
*DOMAIN TIP MEMORY

FIGURE 5

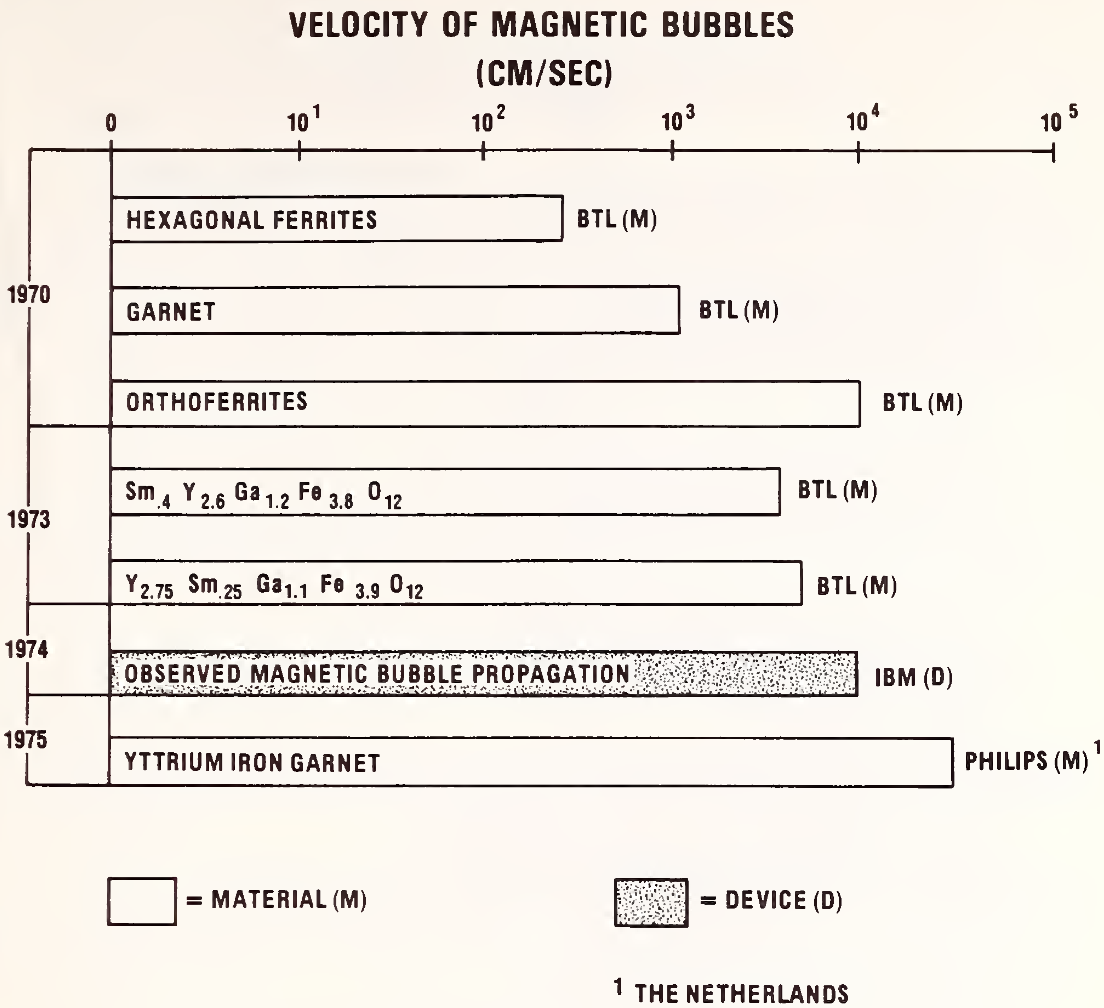

VELOCITY OF MAGNETIC BUBBLES
(CM/SEC)
0
10 1
10 2
10 3
10 4
10 5
1970
HEXAGONAL FERRITES
BTL (M)
GARNET
BTL (M)
ORTHOFERRITES
BTL (M)
1973
Sm .4 Y 2.6 Ga 1.2 Fe 3.8 O 12
BTL (M)
Y 2.75 Sm .25 Ga 1.1 Fe 3.9 O 12
BTL (M)
1974
OBSERVED MAGNETIC BUBBLE PROPAGATION
IBM (D)
1975
YTTRIUM IRON GARNET
PHILIPS (M) 1
= MATERIAL (M)
= DEVICE (D)
1 THE NETHERLANDS

FIGURE 6

DATA RATE OF MAGNETIC BUBBLES (HERTZ)

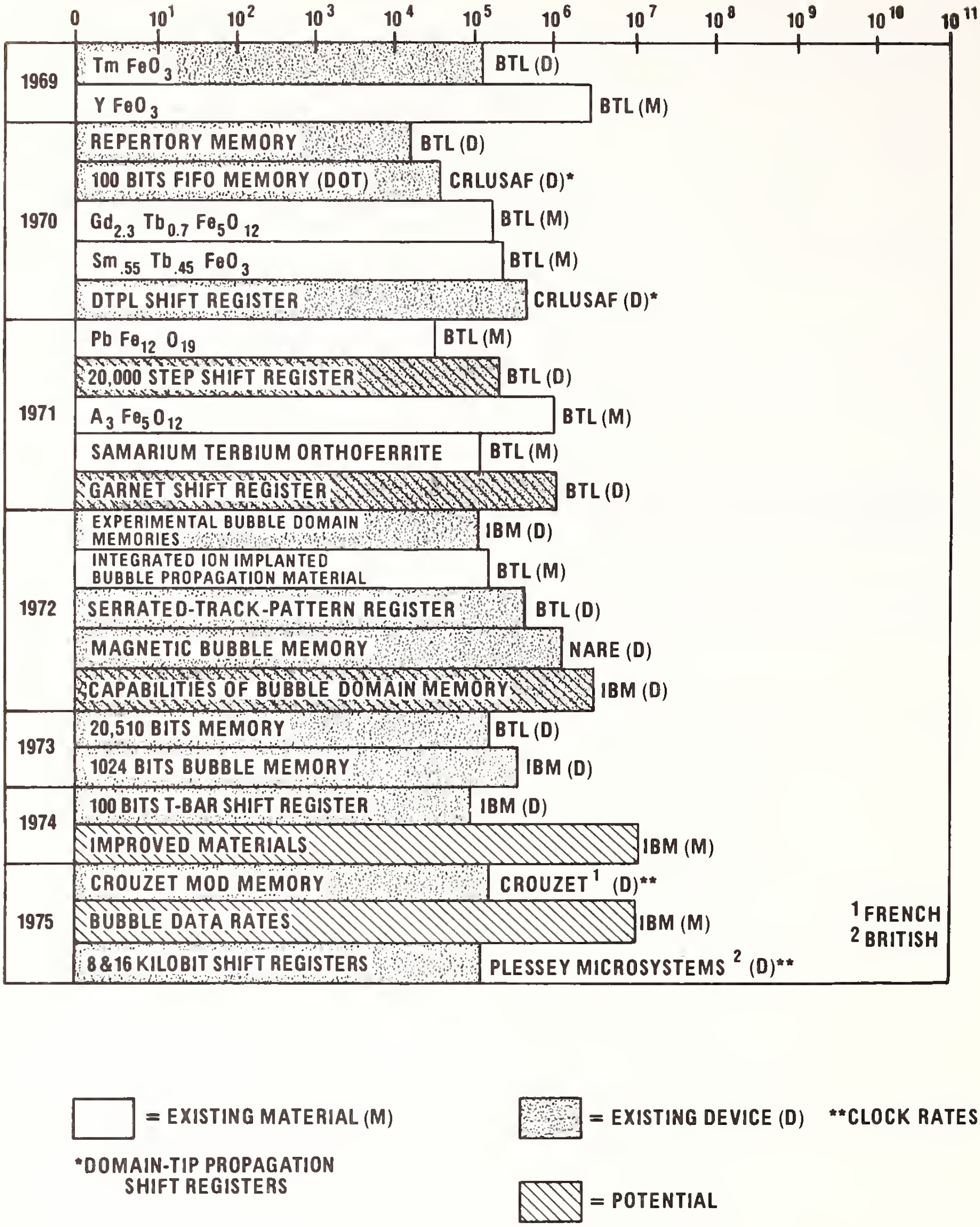


FIGURE 7

The data rate of the bubble, or its propagation speed, has not improved as fast as one would expect. Many sources indicate that the average data propagation rate for present devices is about 10^5 Hertz. If there is to be a marked increase in this data rate, materials with extremely low coercivity and high stability will have to be developed. Unless semiconductor device speed can be attained, long bubble access time may preclude the use of magnetic bubble devices for main computer memories. [8]

Magnetic Bubble Device Power Dissipation

Magnetic bubble devices operate at very low power levels. For example, it is estimated that a bubble bit dissipates several hundred times less power than even the smallest transistor. Figure 8 gives power dissipation data on four examples of bubble memories and indicates that the average power a bubble dissipates (i.e., the energy used to form and control a bubble) is approximately one microwatt. According to one source, the power to perform 10^{12} binary operations a second in magnetic bubble devices would be only 0.04 watt as compared to 10 watts needed by semiconductor switches. [41]

Magnetic Bubble Device Prices

Figure 9 graphs the price trends of magnetic bubble devices and systems. For devices produced in 1972 through 1974, the projected average price was about 0.025 cents per bit. Predictions have been made that future bubble memory systems (including total interface capabilities) could be priced for as little as 0.029 to 0.075 cents per bit. [7, 11]

3. FOREIGN MAGNETIC BUBBLE TECHNOLOGY

Magnetic Bubble Technology in Japan

Although Japanese companies have been studying the magnetic bubble developments for a long time, they did not become heavily involved in this field until the early 1970's. During this period, less-promising orthoferrite magnetic bubble materials were bypassed in favor of garnet films.

The Japanese government is now actively supporting and subsidizing magnetic bubble research. Acting primarily through the Ministry of International Trade and Industry (MITI), a program has been instituted which addresses the following facets of the magnetic bubble technology: [42]

(a) Materials: Garnets and (more recently) the non-crystalline alloys are being investigated. [26, 43, 44]

(b) Bubble guides: Ion implantation and permalloy research is being performed. [33]

(c) Bubble detectors: Efficient Hall effect and magnetoresistive bubble detectors have been developed. [33]

(d) Bubble density: The latest materials are being studied which is resulting in the production of high bit density bubble memory chips. [45]

(e) Packaging techniques: Unique packaging techniques which allow the mass production of bubble devices have been developed.

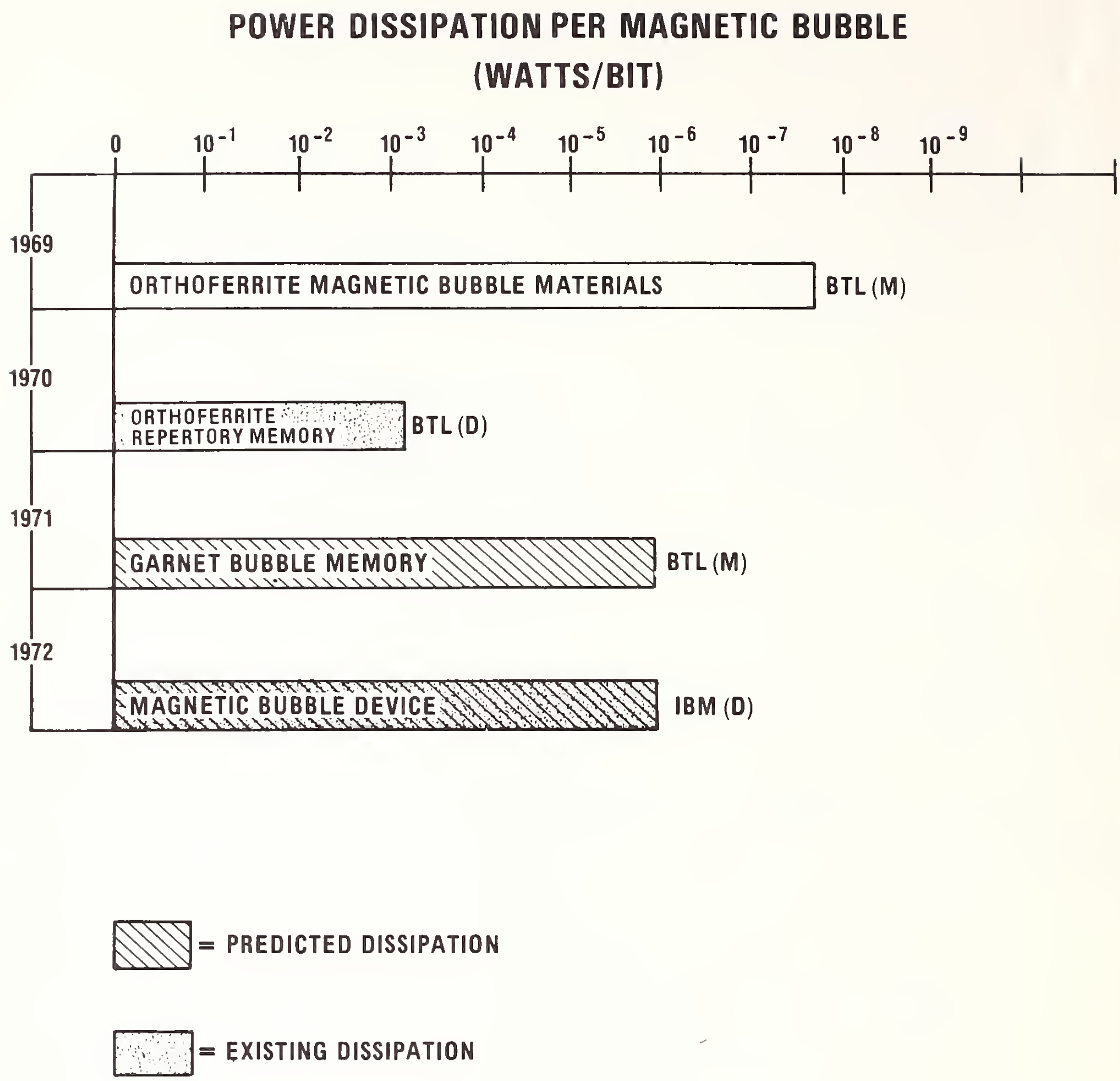

POWER DISSIPATION PER MAGNETIC BUBBLE
(WATTS/BIT)
0
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
1969
ORTHOFERRITE MAGNETIC BUBBLE MATERIALS
BTL (M)
1970
ORTHOFERRITE REPERTORY MEMORY
BTL (D)
1971
GARNET BUBBLE MEMORY
BTL (M)
1972
MAGNETIC BUBBLE DEVICE
IBM (D)
= PREDICTED DISSIPATION
= EXISTING DISSIPATION

FIGURE 8

MAGNETIC BUBBLE DEVICE PRICES
(CENTS/BIT)

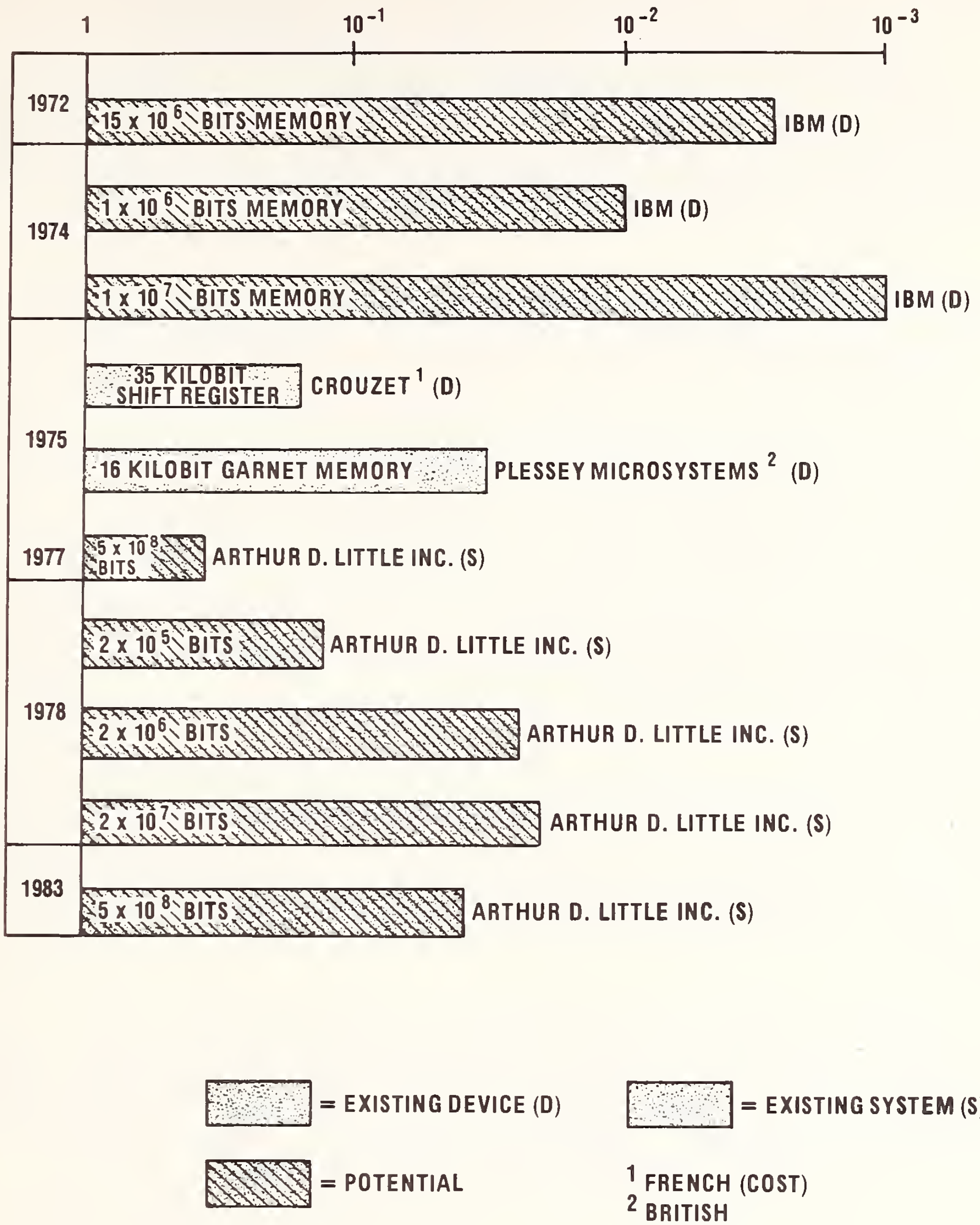


FIGURE 9

(f) Mass production techniques: Unique automatic methods have been perfected which allow mass inspection for flaws in garnet films.

(g) Applications: Many application studies in Japan indicate an intent to introduce bubble memories as replacements for the fast computer auxiliary memories such as disks or drums and memories for small office machines. [12, 45]

The following Japanese research and manufacturing facilities are involved in efforts which collectively provide a complete design structure for the Japanese approach to the magnetic bubble device technology:

- Hitachi Ltd.
- Kokusai Denshin Denwa Co. (KDD)
- Electrotechnical Laboratory
- Nippon Electric Co., Ltd. (NEC)
- Nippon Telegraph and Telephone Public Corp. (NTT)
- Tohoku Metals Industries
- Fujitsu Laboratories, Ltd.

Each of these facilities is involved in a particular phase of the magnetic bubble technology; one researches garnets and another non-crystal alloys, while others concentrate on applications, packaging, and mass production techniques. [24, 26, 33, 42, 43, 46]

Garnet material research has been conducted at the laboratories of Hitachi since 1971. The Faraday rotation effect of the bismuth (Bi) substituted rare earth garnets was studied in great detail by Hitachi. Various material samples were measured for Faraday rotation and optical absorption. The experiments were successful and material samples (such as $Gd_{2.0}\ Bi_{1.0}\ Fe_5\ O_{12}$) with low optical absorption characteristics and good Faraday rotational characteristics (up to 80 degrees of rotation) were identified. In research done by Hitachi, lead (Pb) was added to the iron garnet in order to improve the Faraday rotation effects. Results indicated that Pb-substituted garnets ($Y_{2.5}\ Pb_{0.5}\ Fe_{4.5}\ Ge_{0.5}\ O_{12}$) produced only half of the Faraday rotational increase that the Bi-substituted garnet material had shown. All samples were prepared by the Japanese Central Research Laboratory (Hitachi). [26, 43]

Other experiments, aimed at the understanding of motion and control of the top velocity limits of magnetic bubbles, were conducted at the Nippon Telegraph and Telephone (NTT) Corporation and the Nippon Electric Company (NEC) respectively. The NTT approach used the deposited conductor techniques to produce bubble motion. The results of the experiments were not fully understood because "the observed bubble motion is not sufficiently explained by an existing theory on bubble dynamics." [46]

NEC made attempts to improve the magnetic bubble velocity. (Previously, the reported velocity of their magnetic bubbles resulted in memory data rates of about 1 MHz maximum.) NEC (as reported in 1973) showed an impressive 2200 centimeter/second Oersted velocity figure for a garnet material which included gallium substitution ($Y_{2.8}$ $Eu_{0.2}$ $Fe_{3.7}$ $Ga_{1.3}$ O_{12}). This reported velocity is about half of what was reported in the U.S. during the same period and approximately 1/20 the value reported by Philips (Netherlands) in 1975. [24]

Advanced research with $Gd_{0.5}$ $Y_{2.5}$ Ga Fe_4 O_{12} garnets was performed by the Electrotechnical Laboratory in 1973 according to the Proceedings of the 5th Conference on Solid State Devices. The effort appeared successful in that "hard bubbles" were suppressed by the use of the advanced ion implantation methods. ("Hard bubbles" usually are undesirable bubbles since they tend to propagate more slowly and behave more erratically than "normal bubbles".) Additionally, this facility produced a Hall effect bubble detector capable of sensing bubbles and producing a signal output of 0.5 millivolt with a good 30 db signal-to-noise ratio. [9, 33]

Hitachi, as reported in the Conference proceedings, also overcame the "hard bubble" problem. In their approach, permalloy was deposited on garnet films. Hitachi found that the strong exchange coupling between the permalloy and garnet caused "hard bubble" suppression. Additional efforts in bubble detection were successfully accomplished through the use of both the Hall effect and magnetoresistive detectors. [47]

With garnets established as bubble hosts, permalloy and ion implantation as bubble "purifiers," and detectors providing the required signal levels, additional Japanese facilities were involved in the bubble device technology. Nippon Electric Co. (NEC) and Tohoku Metals were reported to be working on 2.4 kilobit garnet memory chips according to Electronic News, July 29, 1974. The government project called for application of these units in a mass filing system (peripheral memory) and a "fast auxiliary memory" system for internal computer memory use. Other reports indicate similar trends for magnetic bubble memory applications. Japanese government specifications require a fast auxiliary memory with a capacity of 10 megabits at access times of 0.1 milliseconds. These specifications also call for a bubble memory capacity of at least 0.25 million bits per chip by 1978. The specific application of the total computer system appears to be in "pattern information processing." [42]

Fujitsu Laboratories, Ltd., is actively involved in developing mass production techniques for magnetic bubble memories. The facility is addressing both mass production automatic quality control and device packaging techniques. A television system is utilized in the quality control phase during which garnet films are automatically scanned for flaws and defects. Special packaging methods developed by Fujitsu allow for the mass production of flat package devices with less heat dissipation problems than conventional magnetic bubble packages.

Kokusai Denshin Denwa Co. (KDD), is currently experimenting with non-crystalline alloys which could eventually support bubbles with densities two orders of magnitude greater than the garnets. According to the article, magnetic domains of "spark-like" formation (unlike the magnetic bubble cylinder) were found with diameters of 1 micrometer (or about five to ten times greater than the "conventional device" bubble diameter). It is interesting to notice that, even though the alloy bubble is 1 micrometer in diameter, the reported bubble density is approximated at only 10^6 bits per square centimeter. Theoretically, the density should be much higher than the reported value. It appears that magnetic bubble manufacturers generally incur fabrication difficulties which result in a relatively high loss in bit-storage-capacities. [44]

No information has appeared on possible applications exploiting the reported capabilities of the alloy material. The ability of the alloy device to operate as a memory with associated logic functions in addition to exhibiting thermal writing characteristics

may warrant the introduction of a non-crystalline alloy device in a variety of applications other than pure memory. The ability for thermal writing, for example, may make it possible to record a film with the use of a camera flash. If this method is successful, magnetic bubble image sensing could compete with the charge-coupled image devices. [44]

Table 2 indicates noteworthy magnetic bubble research facilities in Japan, their responsibilities, and goals. As indicated, mass production of magnetic bubble memories by Japanese companies can be expected in the near future. The recent announcement by Hitachi of their 64 kilobit memory chip is a strong indication of the present capability in Japan. The formal announcement to be given within the near future will claim that the Japanese device is "among the best in the world". [45]

Development of the 64 kilobit device was funded by the Ministry of International Trade and Industry (MITI). The Hitachi chip, which is to be integrated into the "Pattern Information Processing System," displays outstanding bubble device characteristics. The chip contains 5 micrometer bubbles and measures about 6 x 6 millimeters. Bit density of the chip approaches 10^6 bits per square centimeter. No information is available from which to estimate the speed of the device, but the Japanese 64 kilobit magnetic bubble chip is claimed to be the best magnetic bubble device available. [45]

A 32 kilobit Hitachi device is slated to be implemented in office machines (terminals, document reproduction machines, calculators, and memory typewriters are likely candidates), point-of-sale machines (cash registers, credit checkers, etc), and character displays by Spring of 1976. The magnetic bubble memories are commercial outgrowths of units originally delivered to NTT. The bit price is estimated at about 0.15 cent for initial systems. The bubble replacement memory system is said by Hitachi to be only 5 percent of the size of the replaced drum memory; to weigh only 10 percent as much; and to consume only about one third as much power. In addition, of course, the magnetic bubble memory has no moving parts.[12] Table 3 provides an overview of how accomplishments in Japan compare with the present state-of-the-art of magnetic bubble technology in the United States.

Magnetic Bubble Technology in Great Britain

After Crouzet of France, Plessey Microsystems (U.K.) was the second corporation found to advertise commercial magnetic domain memories. Plessey, however, was the first producer to announce commercial magnetic bubble products.

Previously, little information on the progress of bubble memories in Great Britain had appeared in the literature.

Some bubble memory designs offered by Plessey should be completely developed by the middle or end of 1976. At this time, it is said that an 8 kilobit and 16 kilobit magnetic bubble shift register will be available. [13]

The Plessey magnetic bubble memories appear to be relatively slow (100 KHz data rate). This results in slow (40 millisecond) data access times when compared to conventional disk and drum memories which already display 15 millisecond access times. Reportedly, Plessey officials are aware of this problem and plan to produce a 4 millisecond, 16 kilobit unit before the end of 1976. A 64 kilobit unit is also under development. [13]

TABLE 2

Magnetic Bubble Technology in Japan
(1975)

Research Facilities	Technological Accomplishments							
(Dates of Publications)	Products	Material	Bubble Guides	Bubble Detection	Bubble Size and Density	Packaging Methods	Mass Production Techniques	Application Studies
Kokusai Denshin Denwa Co. KDD (1975)		Non-crystal Gd Fe Alloys			1 micrometer @ 1.25 x 10^6 bits/cm^2			
Hitachi (1973-1975)	16 & 64 kilobit memory chips	Garnet	600-1000°A Permalloy	Hall Effect and Magnetoresistive	5 micrometers @ 10^6 bits/cm^2		(64-kilobit is advertised to be ready for mass prod.)*	Computer Memories, Disks, and Drums
Fujitsu Laboratories (1974)						Garnet Chip Flat Pack Packaging	Automatic Garnet Flaw Detection	
Nippon Electric Co. NEC (1974)	2.4 kilobit memory chips							Mass Memory Filing Systems
Tohoku Metals (1974)	2.4 kilobit memory chips							Mass Memory Filing Systems
Electrotechnical Laboratories (1973)		Garnet ($Gd_{0.5}$ $Y_{2.5}$ Ga Fe_4 O_{12})	Ion Implantation	Hall Effect Detector			Ion Implantation Techniques	

*Probably the first commercially available Japanese product.

TABLE 3

Magnetic Bubble Technology Accomplishments
in Japan and the United States
(1975)

Location of Facility	Products	Materials	Bubble Guides	Bubble Detection Methods	Bubble Size and Density	Memory Data Rate	Commercial Packaging Techniques	Other Commercial Mass Production Techniques
Japan	16 & 64 kilobit memory chips	Garnets and non-crystal alloys	Permalloy and Ion Implantation	Hall Effect and Magneto-resistive*	5-10 micrometer and 10^5 bits/ cm^2 in garnet. 1 micrometer and 1.25×10^6 bits/cm^2 in non-crystal alloy.	1 MHz	Mass Flat Packaging Methods	Automatic Mass Garnet Flaw Detection
United States	16 & 20 kilobit memory chips (64 kilobit experimental chips)	Garnets and non-crystal alloys	Permalloy and Ion Implantation	Magneto-resistive	2-10 micrometer and 10^5 bits/ cm^2 in garnet. 1 micrometer and 10^7 bits/cm^2 in non-crystal alloy.	<1 MHz	None Found	None Found

* U.S. Patent (Hsu Chang, IBM)

Plessey's magnetic bubble memories are all fabricated from garnet material that have been researched since 1972. The substrates are single-crystal gadolinium gallium garnets coated with samarium-doped yttrium iron garnet. A significant factor is that Plessey is offering their products in dual-in-line (DIP) packages. The DIP approach, used for at least ten years in current integrated circuitry components, allows for easy integration of bubble memories in present day designs. [22, 48]

According to an article in Electronics, Plessey's magnetic bubble memories are aimed at a bank data-capture system at an advertised price of 0.1 to 0.01 cent per bit. The replacement magnetic bubble memory systems will probably make use of major and minor loop architectures--the design mentions "transfer gates"--to achieve the desired 4 millisecond access time. Such efforts require state-of-the-art knowledge of magnetic bubble behavior and materials. [13, 36]

The 4 millisecond access times of the proposed Plessey devices still do not meet the 1.5 millisecond access time used by some technology forecasters as a criteria for disk and drum replacements. Therefore, the commercial venture of Plessey into the magnetic bubble memory market with the advertised access times could entail great financial risks.

Magnetic Domain Technology in France

Crouzet (SA) of France, is presently producing moving domain memory cards at a cost of about 0.2 cent per bit. These moving domain (MOD) memories are similar to the conventional magnetic bubble memories; however, they are nonvolatile and need no external magnetic bias fields to form and hold the domains as do magnetic bubble memories. In addition, MOD memories can be fabricated by using conventional thin-film microcircuit techniques. The drawback of slower data rate times and lower bit densities cause MOD memories to be generally considered inferior over magnetic bubble memories. [49]

Crouzet has produced a 2 megabit image-refresh memory. The refresh memory system will be integrated into a military digital television system. Other systems to be delivered include an avionics display refresh memory and a prototype for a satellite memory. The latter systems exploit the magnetic domain memory advantages of low volume, light weight, and low power operation. In addition, since MOD memories are solid-state devices, the lack of mechanical maintenance results in extremely low failure rates. [14]

The MOD memories in France are not fabricated on exotic substrates. Nickel-cobalt is deposited on glass substrates which measure 63 millimeters by 54 millimeters at 0.5 millimeter thickness. Each chip has a 35,000 bit capacity with an average access time of 6 milliseconds. A future line of improved MOD's will have access times of 0.3 milliseconds.

Crouzet will be aiming at the small disk market with a high performance MOD memory replacement. Large disk replacement by MOD memories is not likely to occur since the low domain bit density of the solid state memory results in either a high cost or a noncompetitive access time machine. [14]

MOD memories can be classified as an intermediate technology which exists between the semiconductor and magnetic bubble memories. Crouzet officials predict that their product will be less costly than charge-coupled devices, but charge-coupled devices operate several orders faster than MOD memories. On the other hand, Crouzet feels that their product competes well with 6 micrometer magnetic bubbles, although magnetic bubble bit density should be at least one or two orders better than MOD memories. [14]

The significant fact, however, is that the French company intends to produce magnetic domain memories commercially. The production cycle of the MOD memories will undoubtedly provide the French with valuable magnetic domain memory manufacturing knowledge. If the MOD memory is an intermediate step toward state-of-the-art magnetic domain memories, the French firm could produce solid state magnetic domain memories for replacement of current TV refresh memory, disk, and drum systems.

Magnetic Bubble Technology in The Netherlands

Unlike the multi-corporation program in Japan, the effort in Holland with magnetic bubbles is pursued through just one facility, Philips. Advanced magnetic bubble research by Philips was first reported in the open literature in the last half of 1971 and deals with unusual magnetic bubbles called "hollow cylindrical domains."

The unusual "hollow cylindrical domains" discovered by Philips differ from the conventional solid bubble domains. Hollow cylindrical domains have center regions whose magnetization is opposite to the rest of the bubble wall while typical solid bubbles exhibit the same magnetization throughout their entire cylinders. [50]

The "hollow bubble" is found in an orthoferrite called $LuFeO_3$ and the description of the hollow domain bubble is found only in the Philips literature. Examination of the hollow bubble structure indicates that these domains could exist in several stable sizes. (Six incremental states were observed which ranged from 400 to 1,000 micrometers in diameter.) The increase and decrease in size (called "rentation") of the hollow bubbles is fully controllable by varying the amplitude of the magnetic bias field.

The implementation of the hollow bubble in a solid state bubble processor could give rise to processing languages other than binary, since the hollow bubble can exist in at least six stable states rather than the conventional two binary states of present processor logic elements. However, up to the present time, no implementation or use of the hollow-bubble phenomenon has been described. [50]

The described results of the Philips' experiments display a considerable knowledge of orthoferrite materials. While most advanced magnetic bubble research facilities are concerning themselves with garnet structures, articles by Philips authors stress the fact that the low magnetic moment and high crystal anisotropy of orthoferrites makes this material attractive for magnetic bubble domain material. This material has been found by most researchers to be inferior to the garnets and is not in general use.

Philips suggests the following applications of materials: [27. 34]

- Spinels - recording heads and microwave devices
- Hexagonal Ferrites - bubble domain devices (2 micrometer bubbles)

. Orthoferrites - bubble domain devices (50-100 micrometer bubbles)

. Garnets - bubble domain devices (0.5-10 micrometer bubbles), microwave devices, and magneto-optic devices.

The following is a Philips listing of crystal-growth processes and some of their drawbacks: [27, 34]

. Sputtering Techniques - produces poor quality for single crystal material

. Hydrothermal Epitaxy - requires complicated setups

. Chemical Vapour Deposition (CVD)- requires critical control of various gas streams

. Chemical Solution - requires long periods of time for processing

. Liquid Phase Epitaxy (LPE) - exhibits material mixing problems

Philips also suggests that the CVD process has probably better potentiality than other techniques. The LPE process, according to Philips, is currently the most commonly used procedure. Some literature from other sources indicates that the LPE process is commonly used since this procedure requires low equipment costs, produces a high yield, and adapts easily to variations in garnet compositions. [34]

Philips deposits layers of garnet with a thickness on the order of 1 to 10 micrometers for use in magneto-optical studies, for applications of magnetic bubbles, and for integrated single crystal optics. The substrates used by Philips measure 20 millimeters in diameter and are 0.5 millimeter thick. (Magnetic garnet film is about 1 to 10 micrometer thick.) After the substrates are polished, they are cleaned by Syton, a product bought from the U.S. Monsanto Corporation. The finished products are further scanned for defects by a scanning electron microscope (SEM). [26, 27]

Despite all of the displayed magnetic domain material knowledge by Philips, no reports have been found which indicate that magnetic bubble products (commercial or military) have been produced and delivered to any customers by this company. It appears that Philips has made a preliminary choice between the production of magnetic bubble devices and charge-transfer devices. The decision appears to have been made in favour of charge-transfer (CT) devices (bucket-brigade and charge-coupled devices) since commercial CT products are presently available from Philips.

Magnetic Bubble Technology in the Federal Republic of Germany

A survey of German literature disclosed very few sources of information relative to magnetic bubble memories. Siemens has sponsored the writing of several articles for technical magazines, and these articles indicate that German-made magnetic bubble prototypes are manufactured primarily from garnet materials. Published photographs show garnet strip domains, magnetic bubbles, and bubble guide patterns. Magnetic bubble diameters are said to be optimized since gallium is added to the garnet material. A film of $Y_{2.6}\ Sm_{0.4}\ Ga_{1.2}\ Fe_{3.8}\ O_{12}$ is deposited on a gadolinium garnet substrate. This formula is identical to that used by Bell Telephone Laboratories. [51]

The German-manufactured magnetic bubble materials host 6 micrometer bubbles, while most advanced magnetic bubble device manufacturers, such as Dutch and U.S. facilities, are capable of producing bubbles measuring less than 2 micrometers in diameter. [16]

Magnetic Bubble guides, which are deposited on garnet structures, form bubble guide paths. The guides are made of permalloy material. X X structures, as opposed to T-bar structures, were used as bubble guides. Such structures are rarely used in current magnetic bubble devices made in other countries.

Magnetic bubble memory data rates for the garnet devices made in Germany appear to be in the 100 KHz to 1 MHz range. Magnetic bubble detectors appear to produce far greater output signal levels than do the competitive devices. Detector output signal levels of 50 millivolts were achieved. Output levels of this magnitude are at least one order higher than values reported by researchers in other countries. It appears that most manufacturers have found that high-level output detectors suffer from instability.

The high sensitivity of the detectors is difficult to explain, especially since the associated data rates are not slow. In the past, manufacturers have increased detector output levels by stretching the initial bubble into large domain strips and then sensing the increased magnetic energy contained in the large domains. Unfortunately, the stretching technique could be somewhat time consuming since the incremental increases of bubble size demands additional operating time. The end result of this stretching process is usually a delayed output of data.

Based upon a sketch of a magnetic bubble memory appearing in an article in Electronik, it appears that no unique approaches to magnetic bubble memory architecture are being employed. In a table which compared several parameters of magnetic bubble disks, charge-coupled devices, and domain tip (DOT) memories, most parameters given were similar to parameters published by non-German sources. However, the magnetic bubble bit density was given at 0.5 to 2.5 kilobits per square millimeter. It is estimated that the bit density should be at least ten times higher if 6 micrometer bubbles exist in the garnet films. The low packing density of the devices indicates a possible manufacturing problem which has not been solved. [16]

Several German firms--no names were given--are reported to be building magnetic bubble prototypes. Magnetic drum and disk replacement is the design goal.

Magnetic bubble memory research is subsidized by the West German government. It appears that several research facilities are heavily involved in producing prototypes on government contracts. However, the open literature contains little information of how the involved facilities are progressing.

4. CONCLUSIONS

Information found in both non-U.S. and U.S. literature indicates that much of magnetic bubble LSI circuits are currently produced from garnet materials rather than from silicon. Silicon semiconductors are most often used in the manufacturing of contemporary LSI circuitry.

Early magnetic bubble devices used orthoferrites initially as media for bubbles, but it is generally reported that these materials exhibit inferior memory characteristics when compared to garnet devices. Therefore, orthoferrites have been dropped by many of the advanced magnetic bubble device researchers. Available information reveals that virtually all major researchers and manufacturers of bubble devices in Japan, Great Britain, The Netherlands, the Federal Republic of Germany, and the United States use nonmagnetic garnet substrates and magnetic garnet films for their bubble devices.

Reportedly, amorphous materials are relative new-comers on the scene of magnetic bubble materials. In many instances, these materials are said to support smaller bubbles with potentially higher operating speeds than bubbles of the current garnet technology. Garnets, however, have already been widely accepted as a result of intensive material research that has been reported for over five years.

Officials of the French company Crouzet announced that nickel-cobalt is the material used in their domain memory devices. According to the announcement, these memories are called moving domain memories (MOD). These MOD memories are said to present advantages over contemporary bubble memories in that less exotic substrate materials (glass) and readily available magnetic films (nickel-cobalt) can be used. In addition, nonvolatility of the stored MOD information is said to be assured without the use of permanent magnets that are necessary for magnetic bubble device data retentivity. However, the advertised access times and bit-storage-densities do not measure up to those of garnet device parameters although the MOD memories are potentially less expensive to produce.

Technical information published by magnetic bubble researchers stress the importance of high data-storage-density and fast data access times as goals for their devices. In addition, bubble researchers claim that the nonvolatility and low-power consumption of the magnetic bubble device packages make this product ideal for portable, battery operated, computing apparatus.

At present, the bit-storage-capacity of a single magnetic bubble garnet chip has reached about 64,000 bits; although manufacturers in the U.S. are capable of producing garnet LSI chips of this density, manufacturers in Japan (Hitachi, etc.) are credited with the first delivery of a production lot of such devices. Bit-storage-density is said to be directly related to bubble diameter. Generally, the smaller the bubble, the higher the bit-storage-density. The garnet bubble chips, produced in Japan, exhibit a 2.7 millisecond access time while potential products in the U.S. are reported to border the 1 millisecond range. Further progress is indicated by predictions that magnetic bubble memories can surpass the 100,000 bits and even the 250,000 bits per chip mark in the near future with yields and costs of equal or better than silicon semiconductor memories. On the other hand, the most optimistic available reports do not predict that magnetic bubble memories can approach semiconductors in operating speed. Therefore, bubbles are thought to supplement semiconductor LSI chips in future electronic systems rather than to displace them.

The application of the bubble device was found to occur first as memory in space and military digital data recorders. This memory application makes use of the high-reliability (no moving mechanical parts), high data-storage-density, low-power-operation, and high-radiation-resistance characteristics of the garnet bubble devices. Future applications that are found in bubble device evaluation reports include desk calculators, hand-held calculators, computer peripherals (disk and drum memories), microminiature bubble displays, and electronic test and measurement devices. Little information was found on the application of magnetic bubble devices other than memory.

According to recent advertisements and publications, the introduction of magnetic bubble memory devices promises a significant impact on electronics systems--especially computers. According to the information contained in Table 4, it appears that manufacturers in Japan, Great Britain, and France are realizing this potential and are gearing up for mass production of magnetic domain memories. Technology forecaster reports, however, are contradictory over the time when bubble memories are to catch on. The more optimistic forecasters claim that garnet bubble device acceptance should take place within the next two to five years.

TABLE 4

Non-U.S. and U.S. Magnetic Domain Devices (1975)

Location of Facility	Material Knowledge	Chip Capacity (kilobits)	Bubble Size (Diameter in Micrometers)	Access Time* (Milliseconds) Per Chip	Mass Production Capability
Japan (Hitachi)	Garnets and Amorphous	16 - 64 kilobit chips	5 micrometers in garnets. 1 micrometer in noncrystal alloys.	2.7 milliseconds**	Yes
United States Industry	Orthoferrites, Garnets, and Amorphous Materials	16 - 20 kilobit chips (higher values in experimental chips)	<1 micrometer in garnets. 0.1 micrometer in amorphous materials.	1 millisecond	None found
Great Britain (Plessey Micro-systems)	Garnets	4 - 8 kilobit chip. 16 - 64 kilobit experimental chips	Estimated @ 10 micrometers in garnets.	40 milliseconds	Yes
France (Crouzet)	Nickel-Cobalt	35 kilobit chips	Estimated @ 6 micrometers.	6 milliseconds	Yes
The Netherlands (Philips)	Garnets, Orthoferrites and amorphous materials	None found	0.5 micrometer in garnets.	None found	None found
The Federal Republic of Germany (Siemens)	Orthoferrites and garnets	None found	6 micrometers in garnets.	None found	None found

* Average Disk Access Time is 15 milliseconds
**In 16 kilobit devices

5. GLOSSARY

Glossary of Terms Applicable to Magnetic Bubble Technology

Amorphous film - a film with a noncrystalline structure.

Angelfish - a bubble guide pattern consisting of a series of permalloy arrowheads by which bubbles are propagated directly in response to the modulation of an external magnetic field which is applied normal to the chip surface.

Bubble - an isolated cylindrical domain which exhibits various magnetic properties.

Bubble device - an independent unit (such as memory or a logic processor) wherein the bubble is the active element.

Bubble host - a material such as a thin-film magnetic garnet epitaxially grown on a nonmagnetic garnet substrate. When exposed to the proper magnetic fields normal to the film surface, the garnet film can sustain small stable areas of reverse magnetization, referred to as bubble domains.

Bubble memory - a storage device in which magnetic bubbles are the active elements.

Coercivity - the characteristic of magnetic material which opposes the demagnetizing effect of an external magnetic field.

Conductor access - a method involving conductors in which currents in the conductors generate the required fields for magnetic bubble propagation.

Direct-optical sensing - a method in which the detector reacts to changes in the intensity of light caused by the passage of a bubble over a light source.

Domain wall - the boundary separating adjacent magnetic domains, which is the transition zone through which the magnetization reverses direction.

Electromagnetic-induction detection - a detection method in which the bubble serves as a tiny moving magnet dipole that induces a voltage in a pickup loop located in the reading head.

Epitaxy - a controlled growth or deposition of a crystalline material having the same crystal orientation as the substrate onto which the deposition is formed.

Evaporation - a process by which alloys are formed when beams of thermally agitated atoms intermingle and condense on the underside of a substrate that is suspended in their paths, each beam rising from a heated dish containing a liquid from one of the elements of which the alloy is composed.

Field-access - a method for propagating bubbles by the use of an external pulsating or rotating magnetic field.

Galvano-magnetism/Electromagnetism - magnetism developed by the flow of electrical current.

Garnet - any hard vitreous crystalline mineral from a group comprised of silicates of calcium, magnesium, iron, or manganese with aluminum or iron. For magnetic bubbles, any material having a garnet-like crystal structure with a formula of $(A)_3\ Fe_5\ O_{12}$, where A is a material such as yttrium or one of the rare earths.

Hall effect detection - a phenomenon in which a voltage appears across a semiconductor slab carrying a direct current when the magnetic field of the bubble acts perpendicularly to the slab (at right angles to the current).

Hexagonal ferrite - any phase containing Fe and having a crystal structure related to, but not necessarily the same as, magnetoplumbite.

In-plane rotation - a rotating magnetic field which is applied parallel to the surface of a magnetic platelet containing bubbles.

Liquid phase epitaxy (LPE) - a process of developing magnetic materials, such as garnets, by dipping a non-magnetic crystal into a solution so that a magnetic epitaxial film or solute crystal grows on the surface of the substrate.

Magnetic thin film - a layer of magnetic material on the order of one micron thick.

Magnetoplumbite - $Pb\ Fe_{12}\ O_{19}$ or any phase, containing Fe, having a similar crystal structure.

Magnetoresistance - the effect in which a change in electrical resistance of a material occurs which results from the presence of a magnetic field.

Magnetorestrictivity - the effect or phenomenon in which a magnetic material develops mechanical strains or stresses when magnetized.

Nonvolatility - a property of storage media indicating a capability of information retention independent of sustained power application.

Nucleation - the formulation of a nucleus or the process of clustering.

Oersted - the oersted (CGS system) is the intensity of a magnetic field in which a unit magnet pole experiences a force of one dyne.

Orthoferrite - generally, a mineral consisting of iron and other materials with an orthorhombic distortion of the perovskite crystal structure, whose chemical formula is $A\ Fe\ O_3$ where A can be any rare earth material such as gadolinium.

Permalloy - a bubble guide material, usually consisting of nickel-iron alloy (Ni Fe), which is deposited on a magnetic material.

Photolithography - a process of depositing images by using photographic techniques.

Sputtering - a process by which groups of atoms are chipped away by impact of material from the surface of a target material having the same composition as that of the desired alloy film, and fall onto a substrate, thus building up the layer of an alloy film.

T-bar - a bubble guide pattern which consists alternately of "T" or "I" shaped patterns of permalloy which are deposited on a magnetic material.

Uniaxial structure - a crystalline configuration wherein the magnetic moment vectors are all aligned in the same direction along an easy axis.

Wafer - a thin platelet of material such as a slice of silicon, germanium, or garnet.

Y-bar - a bubble guide pattern which consists of permalloy Y's and bars alternately deposited on a magnetic material.

Glossary of Memory Terms

Access time - the time between input memory addressing and output information availability.

Angstrom - a unit of measurement of wavelength equal to 10^{-4} micrometer or 10^{-8} centimeter.

Associative memory - a memory which produces addresses of words based on the contents of words, rather than the contents of words based on addresses of words; also referred to as content-addressable, catalog, or search memory.

B-H curve - a plot of flux density (B) versus magnetizing force of a magnetic material which shows the characteristic hysteresis loop.

Bipolar memory - a memory in which the storage element utilizes devices such as transistors whose conduction involves both minority and majority carriers.

Bit density - a measure of the number of bits stored per unit of length or area in the storage medium.

Bit plane - a screen or 2-dimensional surface each layer of which contains one bit associated with many words.

Block transfer - the transmission of a group of consecutive words considered as a unit from one plane to another.

Cache - a high-speed memory whose contents are continually updated in blocks from a larger, slower memory to make the effective memory access time approach that of the higher speed (cache) memory.

Charge-coupled device - a semiconductor device which propagates signals by the movement of charge packets.

CMOS (Complementary-Metal-Oxide-Semiconductor) - circuitry and logic employing both P-channel and N-channel MOS transistors with opposite, or complementary, switching characteristics.

Coincident current selection - the addressing, or selection, of a magnetic memory element for reading or writing by the simultaneous drive from two or more current sources.

Content addressable memory - (see associative memory).

Core - a magnetic toroid, usually a ferrite, capable of being magnetized and remaining in one of two conditions of magnetization, thus capable of providing information storage.

Destructive readout - a reading process that destroys the information that has been read out.

Direct access - a method which access to the next piece of information is not dependent upon the last accessed source of information.

Dynamic cell - a storage cell where stored information is affected by time.

Easy axis of magnetization - a preferred direction of magnetization in a magnetic material.

ECL (Emitter-Coupled Logic) - a nonsaturated structure logic where the multiple gate inputs are coupled together by their respective emitters.

Error rate - the total number of errors divided by the total number bits transmitted.

Flux density - the number of magnetic lines of force passing through a unit area.

Full-select current - the total current required in a selection winding or windings through a magnetic core to saturate the core.

Half-select current - approximately one-half the total current required in a winding or windings through a magnetic core to saturate the core.

Hard-axis of magnetization - a direction of magnetization perpendicular to the easy axis of magnetization of a material.

Head gap - the spacing in the magnetic circuit of a record/reproduce head from which the fringing fields emanate.

Hysteresis loop - a graph showing a plot of flux density in a magnetic material on the ordinate and the magnetizing force which produces the flux on the abscissa.

Latency - a delay time in accessing information from a storage device.

Logic speed - the typical logic gate-to-gate propagation speed or clock rate.

LSI (Large-Scale-Integration) - a silicon (or other material) chip containing many gates.

Mass memory - storage devices such as drums, disks, tapes, etc., which are capable of storing large quantities of information.

Memory bus - one or more conductors used as a path over which information may be transmitted from any of several memories to any of several computer system destinations.

Memory capacity - the number of bits, bytes, words, or other elementary quantity of data that can be stored in a memory device.

Memory port - an interface allowing access to the contents of a memory.

MOS (Metal-Oxide-Semiconductor) - a field-effect transistor where the gate is insulated from the channel between source and drain by a metal oxide.

MTBF - "Mean-Time-Between-Failures" (abbreviation).

MTTR - "Mean-Time-To-Repair" (abbreviation).

Nondestructive readout - the sensing of information contained in a storage device without significantly changing the physical representation of the stored information.

Paging - the grouping of storage segments by page and transferring these pages back and forth between main memory and the slower, larger backup memory.

Partial switching - the flux change in a core resulting from the application of partial read or partial write pulses.

Plated wire memory - memories which are obtained by depositing a material such as permalloy in the form of thin-film on a wire.

PROM (Programmable-Read-Only-Memory) - a memory having factory or user programmed contents which are only capable of being read.

RAM (Random-Access-Memory) - a memory capable of being addressed in any sequence for either reading or writing.

Remanent magnetization - the state of magnetization of a material after the external magnetic field has been removed.

ROM (Read-Only-Memory) - a memory having preprogrammed contents capable of being sensed or read only.

Saturation - the magnetic state of a material beyond which an increase in the magnetization is not possible.

Semiconductor memory - a memory whose basic storage elements are semiconductor devices.

SOS (Silicon-On-Saphire) - a metal-oxide-semiconductor circuit developed on an insulator (sapphire) base.

Thin-film memory - a memory that utilizes magnetic thin-films deposited on materials such as glass.

Transfer rate - the rate at which elements of information are transmitted in sequence from source to destination.

TTL (Transistor-Transistor Logic, or T^2L logic) - a standard integrated logic structure consisting of interconnected transistors.

Virtual storage - a combination of hardware and software which automatically allows programmers to program the combination main memory and mass memory as if they were one large main memory.

Volatile storage - a memory device which loses data when power is removed.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This document assesses the status of magnetic bubble technology as displayed by non-U.S. research and manufacturing facilities. Non-U.S. research and U.S. accomplishments are described while both technical and economic factors are addressed. Magnetic bubble devices are discussed whenever their application could impact future computer system design. Generally the magnetic bubble device can be applied to a computer system as a peripheral mass memory. Magnetic bubble devices are produced from either synthetic garnet or amorphous materials rather than from familiar silicon material. The document contains a significant bibliography to support certain main points which are supplemented by information supplied by the library of the Information Technology Division (ICST-NBS) and from private interviews with various U. S. technical experts.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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